Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37627.1

Subslab mantle of African provenance infiltrating the Aegean mantle wedge

Martijn Klaver*, Gareth R. Davies, and Pieter Z. Vroon

Department of Geology and Geochemistry, VU University Amsterdam, De Boelelaan 1085, 1081HV Amsterdam, The Netherlands

*present address: Bristol Isotope Group, School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK; martijn.klaver@bristol.ac.uk

ABSTRACT

The presence of a tear in the subducting African slab has a strong effect on Neogene magmatism in western Turkey, but its influence on volcanism in the Quaternary Aegean arc to the west is unknown. In order to investigate to what extent arc volcanism can be affected by slab-parallel mantle flow from a slab window, we present new trace element and Nd-Pb isotope data for Nisyros and Santorini. Trace element modeling allows quantification of the infiltration of trace element enriched mantle of subslab provenance through the slab tear into the depleted Aegean mantle wedge. Primitive Nisyros magmas record melting of a mixed source that contains up to 10% of the enriched, subslab mantle component and a contribution of this component can be traced as far west as Santorini, ca. 250 km away from the slab tear. We conclude that trace element and Nd-Pb variations between Nisyros and Santorini do not require along-arc variations in subducting sediment composition, but reflect the heterogeneous nature of the Aegean mantle wedge related to infiltration of subslab mantle through the slab tear. Our geochemical evidence is in excellent agreement with predictions made on the basis of mantle tomography and anisotropy, which indicate toroidal mantle flow around the edge of the Aegean slab. This implies that suction related to slab rollback can lead to the infiltration of subslab mantle material and slab-parallel mantle flow, thus potentially strongly influencing arc volcanism, processes that perhaps need greater assessment in other arc systems.

INTRODUCTION AND SETTING

The Mediterranean region is unique as it is the only contemporary example of a subduction zone system with active arc volcanism on the verge of continent-continent collision of Africa and associated microplates with Eurasia. Rollback of the African slab caused back-arc extension, rotation and slab segmentation along the length of the Mediterranean (e.g., Wortel and Spakman, 2001; Van Hinsbergen et al., 2014). In the Aeolian island arc and the Italian peninsula, subduction zone volcanism is strongly influenced by interaction with trace element enriched sub-continental lithospheric mantle (SCLM) and asthenospheric upwelling through multiple tears in a fragmented African slab (Peccerillo et al., 2013). Further east, the Aegean is an extensional regime since the Oligocene, which led to the exhumation of the Cycladic and Menderes core complexes (Fig. 1). Differential movements between the Aegean and

Anatolia, in response to jamming of the subduction zone south of Cyprus, caused splitting of the African slab into an Aegean and a Cyprus branch since ca. 15 Ma (Jolivet et al., 2013). This slab tear and associated rise of hot subslab mantle have been successfully imaged in tomographic studies (e.g., Biryol et al., 2011). Asthenospheric upwelling through this slab window has increasingly influenced magmatism in western Anatolia directly overlying the tear (Agostini et al., 2007; Dilek and Altunkaynak, 2010; Prelević et al., 2012; Ersoy and Palmer, 2013), culminating in the eruption of the Quaternary Kula alkali basalts (Fig. 1; Grützner et al., 2013; Aldanmaz et al., 2015). Given the considerable distance of the central-eastern volcanic centers Nisyros (~100 km) and Santorini (~220 km) to the slab tear (Fig. 1), Quaternary Aegean arc volcanism is considered unaffected by a subslab asthenospheric component and along-arc geochemical variation is proposed to derive from heterogeneous subducting sediments (Ersoy and Palmer, 2013; Elburg et al., 2014). We present new geochemical data for Nisyros and Santorini that provide compelling evidence for mantle wedge heterogeneity and argue that Aegean arc volcanism is strongly controlled by the infiltration of subslab mantle, despite the >100 km distance to the slab tear.

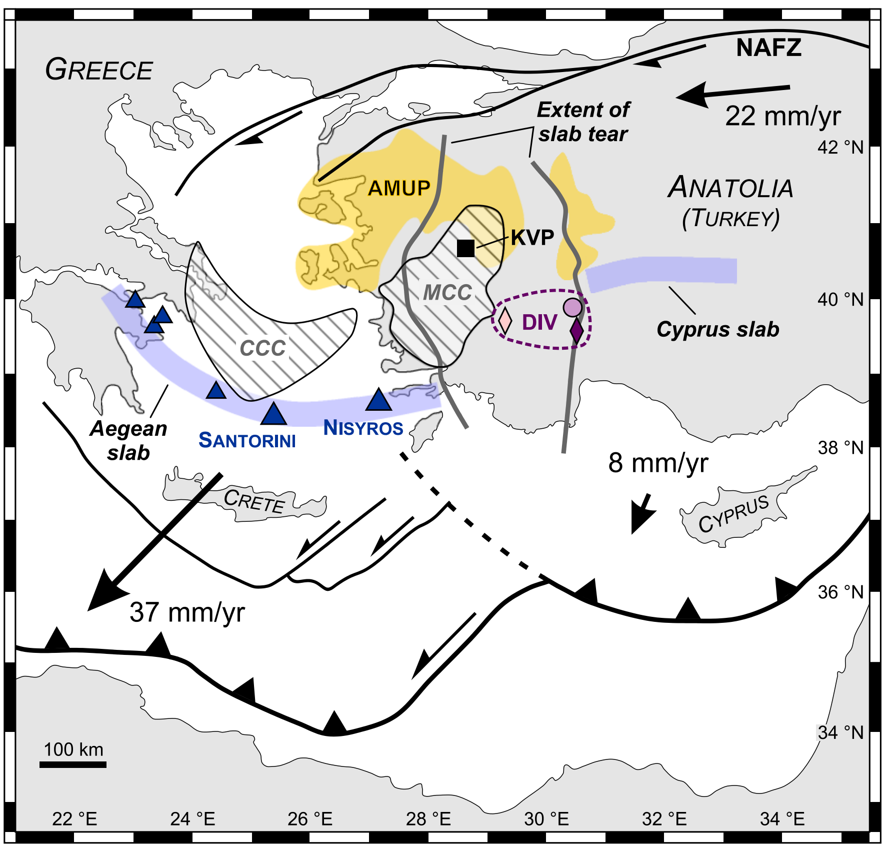

Figure 1. Map of the Eastern Mediterranean highlighting the main features discussed in this study. The translucent blue bands depict the location of the African slab at 150 km depth (Jolivet et al., 2013). The outline of the tear in the African slab is taken from Biryol et al. (2011). Black arrows show GPS determined plate velocities after Doglioni et al. (2002). Hatched areas indicate regions of Neogene extension: CCC –

Cycladic core complex, MCC – Menderes core complex. The shaded yellow area (AMUP – Anatolian Miocene (Ultra-)potassic province) shows the extent of Miocene shoshonitic to (ultra-)potassic volcanism in western Anatolia (Ersoy and Palmer, 2013; Prelević et al., 2015). DIV – Pliocene to Quaternary Denizli-Isparta volcanism; KVP – Kula volcanic field (Quaternary alkali basalts); NAFZ – North Anatolian Fault Zone. The Quaternary volcanic centers of the Aegean arc are shown as blue triangles.

ANALYTICAL TECHNIQUES

We studied 17 samples from Santorini and Nisyros volcanoes (Fig. 1) for high-precision trace element and Pb-Nd isotope analysis following the procedures described in Klaver et al. (2015). In order to minimise the effects of fractional crystallization and assimilation of arc crust, samples are restricted to basalts and basaltic andesites with <57 wt.% SiO_2. High-precision Pb isotope data were obtained using a ^{207}Pb-^{204}Pb double spike to correct for mass fractionation (Klaver et al., 2016). Analytical results, internal and external standards are listed in the online supplementary material. Reproducibility of the trace element ratios shown in Fig. 2, as deduced from repeated analysis of USGS reference material BCR-2 over the course of this study, is better than 3.3% (2 RSD).

RESULTS AND DISCUSSION

The trace element data show marked differences between primitive samples from Santorini and Nisyros. In general, Nisyros has a HFSE and HREE signature that resembles trace element enriched ocean island basalts (OIB) with low Zr/Nb and high Zr/Hf, Nb/Yb, Nb/Ta, Dy/Yb and La/Yb, whereas Santorini largely overlaps with normal mid-ocean ridge basalts (N-MORB) for these ratios. In a Th/Yb versus Nb/Yb diagram (Fig. 2a), samples from both volcanic centers are displaced from the MORB-OIB array toward elevated Th/Yb, a characteristic of arc basalts. Trends defined by Santorini and Nisyros project toward a common component at higher Th/Yb and Nb/Yb, which comprises subducting Eastern Mediterranean Sea sediments that are delivered to the mantle wedge during subduction. As the differentiation trends for Nisyros and Santorini converge toward this component, it is unlikely that they arise from heterogeneity of the subducted sediment component. Instead, the two volcanoes appear to originate from different mantle wedge sources. Primitive Nisyros samples record derivation from a more trace element enriched mantle source compared to Santorini with lower Zr/Nb (~12; Fig. 2b) and higher Nb/Yb (~4; Fig. 2a), Dy/Yb (~1.8) and Nb/Ta (~19) compared to Santorini (~25, 1.5, 1.6 and 14 respectively) and typical N-MORB (32, 0.76, 1.5 and 14; Sun and McDonough, 1989; Münker et al., 2003). In the trace element diagrams in Fig. 2, the Nisyros samples project toward the Kula alkali basalts that are unambiguously related to the upwelling of enriched subslab mantle, suggesting that Nisyros magmatism was also influenced by the slab tear beneath western Anatolia (Fig. 1).

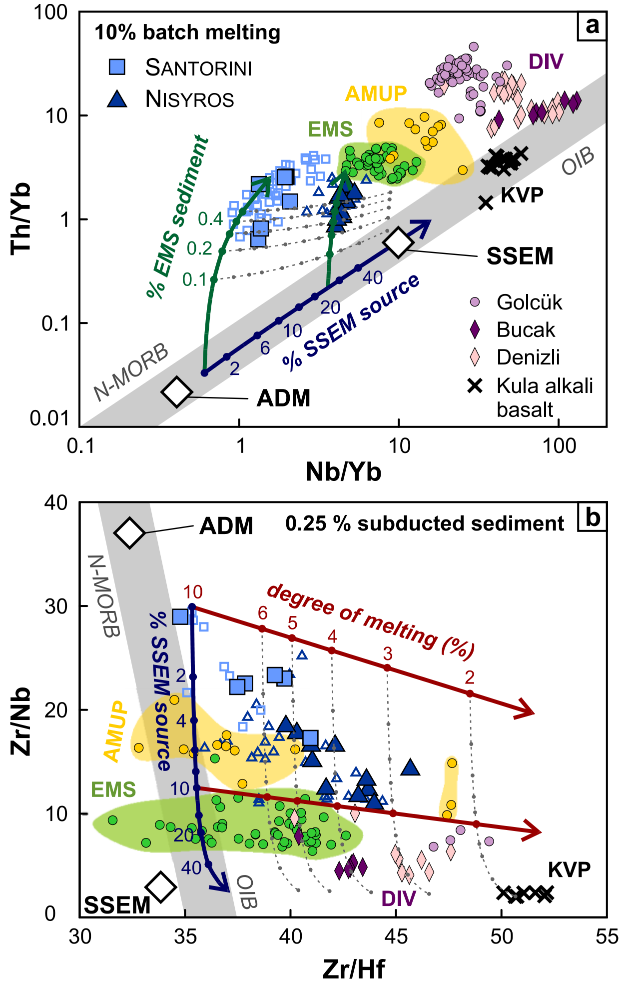

Figure 2. Th/Yb versus Nb/Yb (a) and Zr/Nb versus Zr/Hf (a) diagrams showing the results of trace element modeling of primitive samples from Nisyros and Santorini (large symbols are new data from this study; open symbols are literature data. Miocene and younger Aegean and Anatolian volcanic rocks (<57 wt.% SiO_2) are included – see Fig. 1 caption for a description of the various components; EMS – subducting Eastern Mediterranean Sea sediments. Data sources in the supplementary material. Nisyros and Santorini have distinct trace element systematics that reflect derivation from a heterogeneous mantle wedge beneath the Aegean arc. In (a), the addition of subducting sediment (green model curve) to a mantle source that is a mixture between Aegean Depleted Mantle (ADM) and Subslab Enriched Mantle (SSEM; blue model curve) is shown at a constant degree of melting (10%). In (b), the red model curve represent variations in degree of melting of a heterogeneous source (blue model curve) with a constant subducting sediment contribution of 0.25%.

Source Modeling

In order to constrain the infiltration of an enriched, subslab mantle component in the Aegean arc, we modeled the effects of melting of a heterogeneous mantle source on trace element systematics of

Santorini and Nisyros (Fig. 2a-b). A detailed account of our approach is provided in the online supplementary material and is summarized here. We modeled variable degrees of melting of a hybrid spinel-lherzolite source that is formed by bulk mixing of Aegean depleted mantle (ADM) with subslab enriched mantle (SSEM) to which a variable amount of subducting sediment has been added. The SSEM component has been obtained by calculating the source composition of the Kula alkali basalts, and agrees well with the West Anatolian Mantle source proposed by Aldanmaz et al. (2006).

The composition of the most depleted Santorini samples (lowest Nb/Yb, highest Zr/Nb) can be explained by 10% melting of a depleted ADM source modified by the addition of ~0.5% of subducting sediments, consistent with previous studies (e.g., Bailey et al., 2009; Kirchenbaur and Münker, 2015; Klaver et al., 2015). Lower Zr/Nb and higher Nb/Yb of the primitive Nisyros samples suggest melting of an enriched, mixed ADM-SSEM source. It is impossible, however, to account for the high Zr/Hf in Nisyros by melting a mixed source to similar degrees as for Santorini (10%). Zr/Hf is strongly dependant on the degree of melting (Fig. 2b; Pfänder et al., 2007) and hence the elevated Zr/Hf in Nisyros suggest that these samples reflect a lower degree of melting. The best explanation of the integrated trace element signature of the primitive Nisyros samples, including the ratios shown in Fig. 2a-b and Nb/Ta and La/Yb, is 4% partial melting of an enriched source comprising 9% of the SSEM component with the addition of 0.15% of subducting sediments.

The roughly linear array formed by Santorini, Nisyros and the Kula alkali basalts in a Zr/Hf - Zr/Nb diagram suggests that a continuum exists between high-degree melting of a depleted (ADM) source and low-degree melting of an enriched (SSEM) source in the central-eastern Aegean arc. Santorini lies toward the depleted end of this continuum but correlated variations in Zr/Nb, Nb/Yb and Zr/Hf indicate the involvement of up to 2% of the enriched SSEM component. Hence, the geochemical signature of the enriched subslab component is most pronounced in Nisyros in the eastern section of the Aegean arc but can be traced at least as far west as Santorini, over 250 km west from the slab tear.

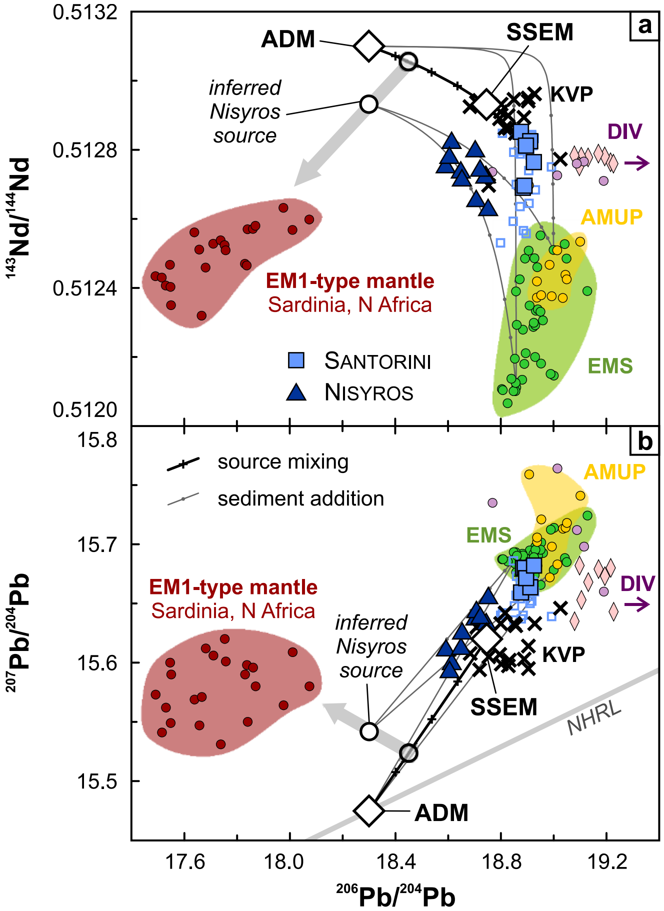

Figure 3. ^{143}Nd/^{144}Nd (a) and ^{207}Pb/^{204}Pb (b) - ^{206}Pb/^{204}Pb diagrams showing the Pb-Nd isotope variation of Nisyros and Santorini. See Fig. 2 for symbols; data for EM1-type mantle component from N Africa and Sardinia from Lustrino and Wilson (2007). The mixing model based on trace element systematics is shown (black line with plusses), as are mixing curves between different mantle source compositions and subducting sediment (gray lines with dots). The mixed ADM-SSEM source (open circle) as obtained from trace element modelling, cannot reproduce the low ^{143}Nd/^{144}Nd and high ^{207}Pb/^{204}Pb of the Nisyros source inferred from Nd-Pb isotopes (filled circle). This offset can be explained by interaction of the upwelling SSEM component with an EM1-type African SCLM at the slab edge.

Pb-Nd Isotope Constraints

Radiogenic isotope variations in primitive Aegean arc magmas are ascribed to the addition of variable amounts of heterogeneous subducting sediment to a homogeneous ADM source, but have not been evaluated in the light of mantle wedge heterogeneity (Bailey et al., 2009; Elburg et al., 2014; Kirchenbaur and Münker, 2015). Variations in subducting sediments, however, fail to explain the unradiogenic ^{206}Pb/^{204}Pb (18.6–18.8) at relatively high ^{207}Pb/^{204}Pb (15.59–15.66) and low ^{143}Nd/^{144}Nd (<0.51285) of Nisyros (Fig. 3; Klaver et al., 2015). On the basis of the trace element modeling, we propose

Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G37627.1

that these features reflect the heterogeneous nature of the mantle wedge in the central-eastern Aegean associated with the slab tear. Addition of subducting sediment to the enriched source comprising 9 % of the SSEM component, as inferred from trace element modeling, fails to reproduce the Nd-Pb systematics of Nisyros (Fig. 3). A suitable source for Nisyros has an Enriched Mantle 1 (EM1) affinity, characterized by high $^{207}Pb/^{204}Pb$ and low $^{143}Nd/^{144}Nd$. Such a component has been recognized in North African basalts and on Sardinia (Lustrino and Wilson, 2007) and could represent the sub-continental lithospheric mantle of the African continent. Interaction of rising asthenospheric mantle with African SCLM at the slab edge is a viable process to have modified the Pb-Nd isotope signature of the upwelling SSEM source.

At first sight, the involvement of a high $^{206}Pb/^{204}Pb$ SSEM component and metasomatized SCLM to generate the lower $^{206}Pb/^{204}Pb$ in Nisyros seems counterintuitive. The explanation lies in the higher Pb content of the enriched source. In conjunction with an overall lower sediment contribution deduced from Th/Yb systematics, the higher Pb content of the mantle source provides an efficient buffer for Pb released from the subducting slab. Hence, these two processes work in tandem and result in a smaller shift toward the Pb isotope composition of subducting sediment in magmas at Nisyros compared to Santorini. In addition, the higher Pb content of the Nisyros mantle wedge suppresses the curvature of the hyperbolic mixing lines (Fig. 3). Thus, the lower $^{206}Pb/^{204}Pb$ characteristic for Nisyros can be explained by derivation from a more enriched mantle source and lower sediment contribution, and does not necessitate along-arc variations in subducting sediment composition, for which there is no evidence (Klaver et al., 2015).

Geodynamical Implications

Rollback of a subducting slab creates a pressure gradient within the asthenospheric and lithospheric mantle as the subslab mantle is compressed whereas a tensional regime develops in the mantle wedge. The latter is accommodated by asthenospheric flow towards the retreating slab. Beneath the Aegean and western Anatolia, pronounced NE-SW anisotropy of the asthenospheric mantle suggests mantle flow toward the Aegean arc (Evangelidis et al., 2011; Olive et al., 2014). The opening of a slab tear as the result of differential movement between the Aegean and Anatolia (Biryol et al., 2011; Jolivet et al., 2013) causes buoyant upwelling of subslab mantle of African provenance, which is enhanced by suction exerted by slab rollback (Sternai et al., 2014). This interpretation is consistent with the regional seismic anisotropy. Paul et al. (2014) noted that the area in SW Anatolia overlying the slab tear is characterized by NW-SE mantle anisotropy, which forms a sharp contrast with the dominant NE-SW direction seen in the Aegean and Anatolia (Fig. 4). This counter clockwise rotation in mantle anisotropy can be directly related to toroidal mantle flow around the edge of the Aegean slab toward the arc front, analogous to, for instance, the Juan de Fuca slab in the western United States (Zandt and Humphreys, 2008) and the Aeolian arc (Peccerillo et al., 2013). Thus, we argue that the geochemical signature of the enriched subslab mantle is not restricted to the area directly overlying the slab tear but will also influence the

Aegean region to the W and SW. Due to SW flow away from the slab tear, the subslab mantle component infiltrates the melt depleted mantle wedge such that the pure SSEM component is only manifested in the center of the tear (Kula alkali basalts). Jolivet et al. (2015) proposed that asthenospheric flow from the slab tear toward the SW is responsible for the formation of late Miocene high-temperature metamorphic domes and magmatism in the northern Cyclades, but its involvement in magma generation in the Aegean arc was not previously proposed. The recognition of an enriched component in the source of Nisyros and Santorini is, however, fully consistent with the presence of a slab tear beneath western Anatolia and toroidal mantle flow around the edge of the Aegean slab, transporting enriched subslab mantle of African provenance into the mantle wedge underlying the central-eastern Aegean arc. Data presented here indicate that the subslab mantle component can be recognized as far west as Santorini, ~250 km from the slab tear.

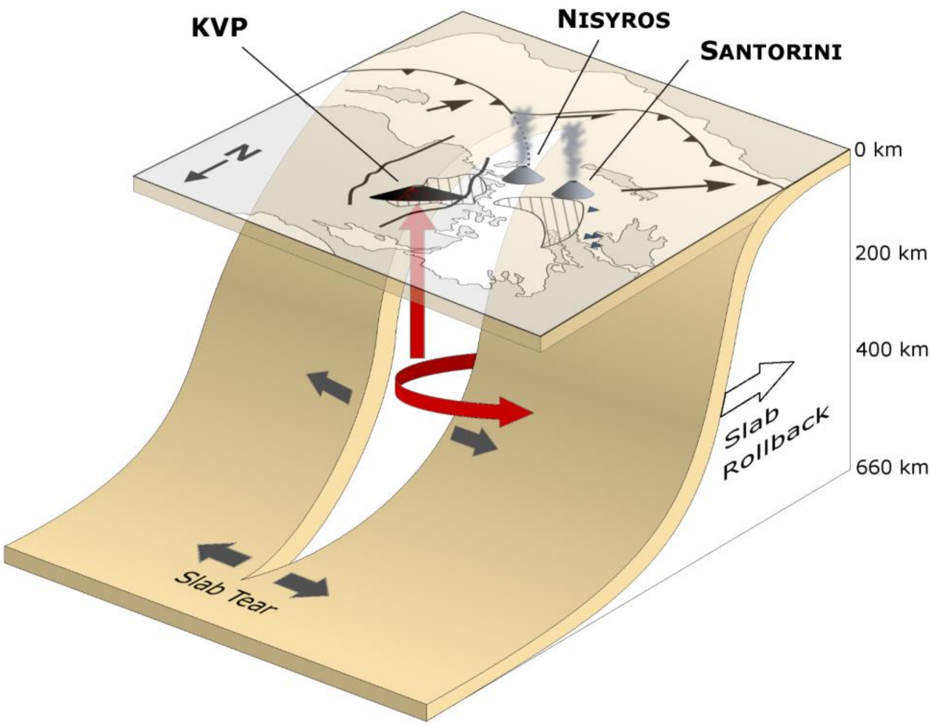

Figure 4. Schematic model showing the toroidal flow of subslab enriched mantle of African provenance around the edge of the Aegean slab. The Kula volcanic province (KVP) is dominated by the upwelling of subslab mantle. Infiltration of this component in the Aegean mantle wedge can be traced as far west Santorini.

ACKNOWLEDGMENTS

Permission for fieldwork on Santorini and Nisyros was kindly provided by the Greek Institute of Geology and Mineral Exploration (IGME). Max Jansen is acknowledged for producing Figure 4 and Richard Smeets, Bas van der Wagt and Roel van Elsas are thanked for analytical assistance. Constructive comments made by Klaudia Kuiper and careful reviews from D. Prelevic, S. Foley and Y. Dilek significantly improved the manuscript.

REFERENCES CITED

Agostini, S., Doglioni, C., Innocenti, F., Manetti, P., Tonarini, S., and Savaşçin, M.Y., 2007, The transition from subduction-related to intraplate Neogene magmatism in the Western Anatolia and Aegean area: Geological Society of America Special Paper 418, p. 1–15, doi:10.1130/2007.2418(01).

Aldanmaz, E., Köprübaşı, N., Gürer, Ö., Kaymakçı, N., and Gourgaud, A., 2006, Geochemical constraints on the Cenozoic, OIB-type alkaline volcanic rocks of NW Turkey: Implications for mantle sources and melting processes: Lithos, v. 86, p. 50–76, doi:10.1016/j.lithos.2005.04.003.

Aldanmaz, E., Pickard, M., Meisel, T., Altunkaynak, Ş., Sayıt, K., Şen, P., Hanan, B.B., and Furman, T., 2015, Source components and magmatic processes in the genesis of Miocene to Quaternary lavas in western Turkey: Constraints from HSE distribution and Hf–Pb–Os isotopes: Contributions to Mineralogy and Petrology, v. 170, p. 23–42, doi:10.1007/s00410-015-1176-x.

Bailey, J.C., Jensen, E., Hansen, A., Kann, A., and Kann, K., 2009, Formation of heterogeneous magmatic series beneath North Santorini, South Aegean island arc: Lithos, v. 110, p. 20–36, doi:10.1016/j.lithos.2008.12.002.

Biryol, C.B., Beck, S.L., Zandt, G., and Özacar, A.A., 2011, Segmented African lithosphere beneath the Anatolian region inferred from teleseismic P-wave tomography: Geophysical Journal International, v. 184, p. 1037–1057, doi:10.1111/j.1365-246X.2010.04910.x.

Dilek, Y., and Altunkaynak, Ş., 2010, Geochemistry of Neogene–Quaternary alkaline volcanism in western Anatolia, Turkey, and implications for the Aegean mantle: International Geology Review v. 52, p. 631-655, doi:10.1080/00206810903495020

Doglioni, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F., and Savascin, Y., 2002, On the extension in western Anatolia and the Aegean sea: Journal of the Virtual Explorer, v. 08, p. 169–183, doi:10.3809/jvirtex.2002.00049.

Elburg, M.A., Smet, I., and De Pelsmaeker, E., 2014, Influence of source materials and fractionating assemblage on magmatism along the Aegean Arc, and implications for crustal growth: Geological Society of London, Special Publications, v. 385, p. 137–160, doi:10.1144/SP385.1.

Ersoy, E.Y., and Palmer, M.R., 2013, Eocene-Quaternary magmatic activity in the Aegean: Implications for mantle metasomatism and magma genesis in an evolving orogeny: Lithos, v. 180–181, p. 5–24, doi:10.1016/j.lithos.2013.06.007.

Evangelidis, C., Liang, W.T., Melis, N., and Konstantinou, K., 2011, Shear wave anisotropy beneath the Aegean inferred from SKS splitting observations: Journal of Geophysical Research: Solid Earth (1978–2012), v. 116, B04314, doi:10.1029/2010JB007884.

Grützner, T., Prelević, D., and Akal, C., 2013, Geochemistry and origin of ultramafic enclaves and their basanitic host rock from Kula Volcano, Turkey: Lithos, v. 180–181, p. 58–73, doi:10.1016/j.lithos.2013.08.001.

Jolivet, L., Faccenna, C., Huet, B., Labrousse, L., Le Pourhiet, L., Lacombe, O., Lecomte, E., Burov, E., Denele, Y., and Brun, J.-P., 2013, Aegean tectonics: Strain localisation, slab tearing and trench retreat: Tectonophysics, v. 597–598, p. 1–33, doi:10.1016/j.tecto.2012.06.011.

Jolivet, L., Menant, A., Sternai, P., Rabillard, A., Arbaret, L., Augier, R., Laurent, V., Beaudoin, A., Grasemann, B., and Huet, B., 2015, The geological signature of a slab tear below the Aegean: Tectonophysics, v. 659, p. 166–182, doi:10.1016/j.tecto.2015.08.004.

Kirchenbaur, M., and Münker, C., 2015, The behaviour of the extended HFSE group (Nb, Ta, Zr, Hf, W, Mo) during the petrogenesis of mafic K-rich lavas: The Eastern Mediterranean case: Geochimica et Cosmochimica Acta, v. 165, p. 178–199, doi:10.1016/j.gca.2015.05.030.

Klaver, M., Djuly, T., de Graaf, S., Sakes, A., Wijbrans, J., Davies, G., and Vroon, P., 2015, Temporal and spatial variations in provenance of Eastern Mediterranean Sea sediments: Implications for Aegean and Aeolian arc volcanism: Geochimica et Cosmochimica Acta, v. 153, p. 149–168, doi:10.1016/j.gca.2015.01.007.

Klaver, M., Smeets, R., Koornneef, J.M., Davies, G., and Vroon, P., 2016, Pb isotope analysis of ng size samples by TIMS equipped with a 1013 ▯ resistor using a 207Pb-204Pb double spike: Journal of Analytical Atomic Spectrometry, v. 31, p. 171–178, doi:10.1039/C5JA00130G.

Lustrino, M., and Wilson, M., 2007, The circum-Mediterranean anorogenic Cenozoic igneous province: Earth-Science Reviews, v. 81, p. 1–65, doi:10.1016/j.earscirev.2006.09.002.

Münker, C., Pfänder, J.A., Weyer, S., Büchl, A., Kleine, T., and Mezger, K., 2003, Evolution of planetary cores and the Earth-Moon system from Nb/Ta systematics: Science, v. 301, p. 84–87, doi:10.1126/science.1084662.

Olive, J.-A., Pearce, F., Rondenay, S., and Behn, M.D., 2014, Pronounced zonation of seismic anisotropy in the Western Hellenic subduction zone and its geodynamic significance: Earth and Planetary Science Letters, v. 391, p. 100–109, doi:10.1016/j.epsl.2014.01.029.

Paul, A., Karabulut, H., Mutlu, A.K., and Salaün, G., 2014, A comprehensive and densely sampled map of shear-wave azimuthal anisotropy in the Aegean–Anatolia region: Earth and Planetary Science Letters, v. 389, p. 14–22, doi:10.1016/j.epsl.2013.12.019.

Peccerillo, A., De Astis, G., Faraone, D., Forni, F., and Frezzotti, M., 2013, Compositional variations of magmas in the Aeolian arc: implications for petrogenesis and geodynamics: Geological Society, London, Memoir 37, p. 491–510, doi: 10.1144/M37.15

Pfänder, J.A., Münker, C., Stracke, A., and Mezger, K., 2007, Nb/Ta and Zr/Hf in ocean island basalts—implications for crust–mantle differentiation and the fate of Niobium: Earth and Planetary Science Letters, v. 254, p. 158–172, doi:10.1016/j.epsl.2006.11.027.

Prelević, D., Akal, C., Foley, S., Romer, R., Stracke, A., and Van Den Bogaard, P., 2012, Ultrapotassic mafic rocks as geochemical proxies for post-collisional dynamics of orogenic lithospheric mantle: The case of southwestern Anatolia, Turkey: Journal of Petrology, v. 53, p. 1019–1055, doi:10.1093/petrology/egs008.

Prelević, D., Akal, C., Romer, R.L., Mertz-Kraus, R., and Helvacı, C., 2015, Magmatic response to slab tearing: constraints from the Afyon Alkaline Volcanic Complex, Western Turkey: Journal of Petrology, v. 56, p. 527–562, doi:10.1093/petrology/egv008.

Sternai, P., Jolivet, L., Menant, A., and Gerya, T., 2014, Driving the upper plate surface deformation by slab rollback and mantle flow: Earth and Planetary Science Letters, v. 405, p. 110–118, doi:10.1016/j.epsl.2014.08.023.

Sun, S.s., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes: Geological Society of London, Special Publications, v. 42, p. 313–345, doi:10.1144/GSL.SP.1989.042.01.19.

Van Hinsbergen, D.J.J., Vissers, R.L.M., and Spakman, W., 2014, Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation: Tectonics, v. 33, p. 393-419, doi:10.1002/2013TC003349

Wortel, M., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917, doi:10.1126/science.290.5498.1910.

Zandt, G., and Humphreys, E., 2008, Toroidal mantle flow through the western US slab window: Geology, 36, p. 295–298, doi:10.1130/G24611A.1.

[1]GSA Data Repository item 2016xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.